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DESIGN AND TEST OF ADVANCED MULTI-LAYER DIELECTRIC GRATINGS FOR HIGH ENERGY PETAWATT

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ABSTRACT

In this paper we discuss recent work on the development of high damage threshold, high efficiency MLD (multilayer dielectric) diffraction gratings for use in high energy, petawatt laser systems. This effort involves a close integration between modeling, fabrication, and testing. The modeling work is used to identify grating designs that satisfy the constraints of high efficiency(>94%) and low field enhancement which is a necessary condition for high damage threshold. Subscale MLD gratings for test are being fabricated in an advanced ion-etch machine we have recently built. The testing effort is being conducted in a dedicated laboratory. The laser beam used to test the samples is based on an OPCPA (optical parametric chirped-pulse amplifier) and a compressor that can provide pulse energies up to 50mJ with pulse lengths variable from 0.3 – 20 ps. This test station is equipped with diagnostics to fully characterize both the spatial and temporal characteristics of the test beam at the plane of the sample. Initial results have demonstrated a dependence of damage threshold on incident angle that is in good agreement with the field enhancement calculations. We have demonstrated a grating design with a damage threshold of 3J/cm^2 and are investigating manufacturability and reproducibility issues as well.

I. INTRODUCTION

The performance of high-energy petawatt laser systems is limited by the damage threshold of the final grating of the pulse compressor which is exposed to the fully compressed pulse. The damage threshold of gold-coated gratings is limited[1] to about 0.4 J/cm^2. Limiting the fluence to this level would require a beam size too large to be practical for many high-energy systems.

For higher fluences, a more promising solution is an all-dielectric grating. The type of grating considered in this paper is shown in figure 1. These gratings can have a damage threshold nearly ten times that of gold gratings.
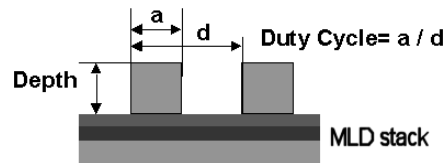

Fig. 1 Schematic of MLD grating.

The theoretical limitation on the damage threshold of an MLD grating exposed to a short pulse results from the damage thresholds of the grating materials in combination with the field distribution in the grating.[2] The measured damage threshold may in addition be affected by such factors as 1) processing methods, e.g. removal of photoresist, 2) deviations between design parameters and manufactured grating, and 3) defects in the grating or multilayer stack. The MLD grating development at LLNL addresses all of these issues.

In the present paper we first discuss the optimization of the grating design to achieve high diffraction efficiency and low field enhancement. Next we discuss the test facility we have developed to conduct damage experiments with pulses with fully characterized spatial and temporal properties. Finally we discuss the results of the tests including verification of the model and the influence of manufacturing processes.

II. GRATING DESIGN OPTIMIZATION

The grating design must satisfy several constraints. The grating must have high dispersion to limit the length of the compressor. The grating size is limited to about 1-m in our facility. This, along with the angle of incidence, determines the maximum beam size. The

damage threshold is also a function of the incidence angle as discussed below. The grating profile and stack must have a high diffraction efficiency into the −1 order. The design must be manufacturable, a constraint that includes the requirement that the performance of any design must be relatively stable to small variations of its parameters.

The grating parameters that can be adjusted are the groove density, depth, shape and duty cycle, the latter being defined in figure 1. The multilayer stack design is also critical to performance. The stack increases the efficiency and also influences the field distribution and therefore the damage threshold.

The grating and MLD stack are modeled using the code "LAMBDA" designed by Lifeng Li and based on a modal analysis which has been documented elsewhere.[3] This model is well suited to the rectangular grooves and TE polarization of interest here. A commercial code, TFCALC, is also used in MLD stack optimization.

The starting point of the design is a 1740-l/mm grating with an incidence angle of 61° (near Littrow). With a groove height of 620-nm and a duty cycle of 0.28, the predicted efficiency is >99%. The MLD stack consists of 20 layers of alternating Ta_2O_5 and Al_2O_3. Figure 2 shows the variation of diffraction efficiency with duty cycle and groove depth. High efficiency is maintained over a large variation of these parameters.
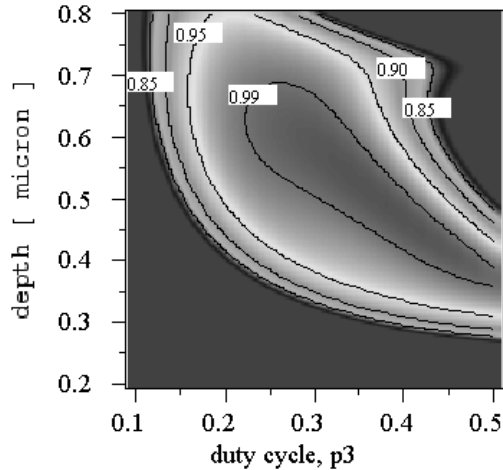
Fig. 2 The efficiency of the grating is above 95% over a wide range of depth and duty cycle variations.

The theoretical limit of the damage threshold occurs when the field in the dielectric materials of the grating exceeds the damage threshold of the material. Figure 3 shows contours of the magnitude of the field in units of the input field magnitude. The maximum field enhancement of 2.3 occurs a few hundred nanometers above the grating surface. The largest field enhancement in the grating materials occurs on the edge of the groove and is about 1.7 times the input field. The damage threshold of this grating then would be about 3 times lower than that of the grating material, SiO_2.
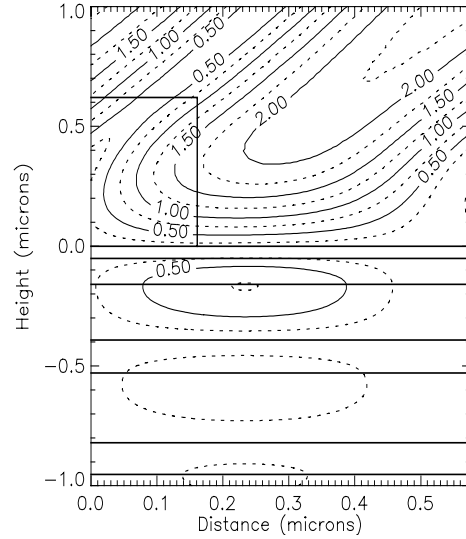
Fig. 3 Field distribution in one period of a 1740 l/mm grating and the top layers of the MLD stack. Height is measured from the top of the stack. The rectangle at the left represents the SiO_2 grating material. The horizontal lines represent the stack layers.

Several parameters were varied in order to improve this damage threshold. A modest (5-10%) improvement results from reducing the duty cycle. Angled grooves were found to have little effect.

The largest improvement found to date results from increasing the incidence angle. Figure 4 shows the field enhancement and efficiency of a 1780-l/mm grating. The field enhancement can be below 1.2 at an incidence angle of 76.7°.
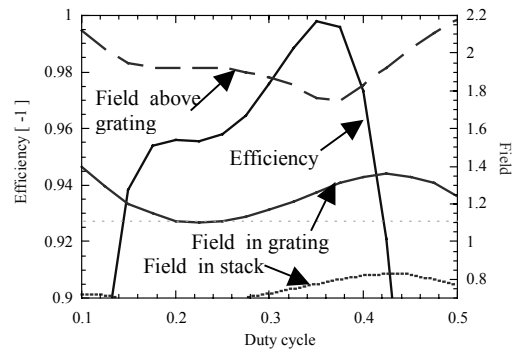
Fig. 4 Efficiency and field enhancement for a 1780-l/mm grating with a groove depth of 650nm and an incidence angle of 76.7°.

III. PRECISION DAMAGE TEST FACILITY

Verification of the model predictions for damage threshold requires a test facility with the capability of fully characterizing the temporal and special properties of the test beam. In this section we describe the laboratory we have recently activated to test subscale (50mm diameter) gratings.

The Precision Damage-Test Facility (PDTF) consists of three main subsystems, the laser source, the diagnostics and the damage-test table. The initial pulse for the laser source is generated by a commercial femtosecond laser, stretched with a grating pair and amplified to about 50mJ in an optical parametric chirped-pulse amplifier (OPCPA). The output pulse can be compressed to ~200fs although for most of the tests here the pulse is only partially compressed to give the desired pulse width. The laser operates at 10 Hz with a pulse-to-pulse energy stability of ±2% (one standard deviation). The details of the laser system will be discussed elsewhere.
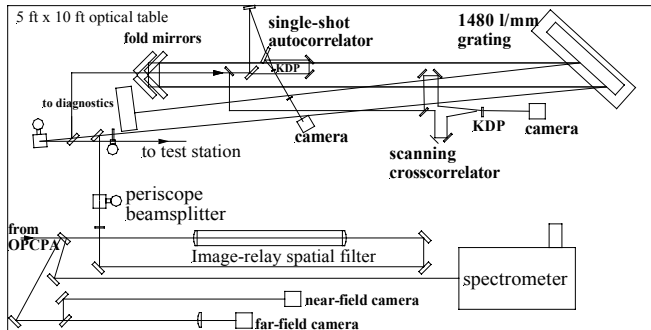

Fig. 4 Layout of diagnostics table of PDTF. The beams in the region of the compressor are at several different levels. The two passes of the main beam and the diagnostic beam are on four different levels about 30 cm above the table. The cross correlator and autocorrelator are about 6 cm above the table.

The compressor/diagnostics table is shown in figure 4. Before compression 4% of the output is split from the OPCPA for a diagnostic beam. The main output beam from the OPCPA is compressed by a 2-pass, folded compressor. The compressor length is adjusted to not fully compensate the dispersion of the pulse stretcher in order to generate the desired pulse duration for the damage test, typically 10ps. The diagnostic beam is injected into a pulse compressor which uses the same grating but a different set of fold mirrors whose distance from the grating can be independently set. The distance of this second set of fold mirrors is set to compress the diagnostic beam to its minimum pulse duration of about 0.25ps. The fully compressed diagnostic beam is mixed with the test beam in a 1mm thick LBO crystal to form a second-order scanning cross correlator. Since the fully compressed pulse is much shorter than the test beam, the cross correlator gives the temporal profile of the test beam without the ambiguities of an autocorrelator. The disadvantage of the cross correlator is that it averages over many pulses. A typical pulse temporal profile measured using the cross correlator is shown in figure 5.

Either the test beam or the diagnostic beam can be directed into a single-shot autocorrelator. This is used both to monitor the pulse-to-pulse stability of the

temporal profile and to determine the pulse duration of the fully compressed diagnostic pulse. The spectrum of the laser is monitored and the measured spectrum is used to deconvolve the autocorrelation trace. The near field and far field spatial profiles of the laser are also monitored. These are primarily used for laser diagnostics. The test beam spatial profile at the sample plane is monitored on the damage-test table discussed below.
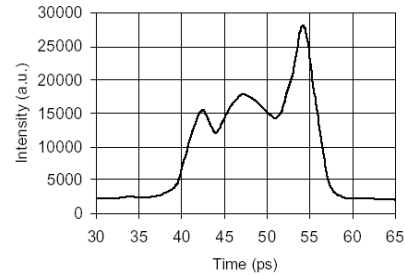

Fig. 5 Typical temporal pulse profile from cross correlator.

The layout of the damage-test table is shown in figure 6. The ~1cm diameter beam from the compressor is focused onto the sample with a 2m focal length lens. A half-wave plate rotates the polarization so all measurements are done using TE polarization. The energy on the sample is monitored with a pyroelectric joulemeter that samples the beam through a partially reflecting mirror. This energy is calibrated using another energy
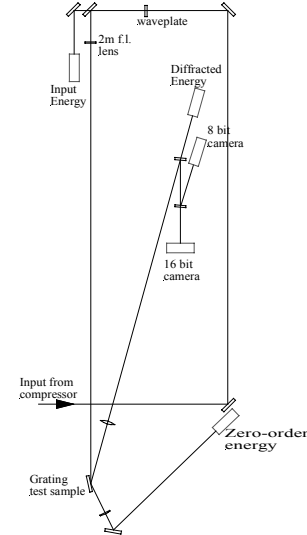

Fig. 6 Layout of damage-test table

meter placed in front of the test sample. Two other joulemeters measure the diffracted −1 order and the zero-order reflection.

The spatial profile of the beam on the sample is imaged onto both a 16-bit camera and an 8-bit camera. The 16-bit camera is used primarily to accurately measure the profile and the energy in the spatial wings of the

beam. These measurements are taken prior to the damage measurement with a flat, fused silica sample at near normal incidence replacing the grating. The 8-bit camera is used primarily to monitor the diffracted beam from the grating on each shot. A typical beam profile at the sample is shown in figure 7.
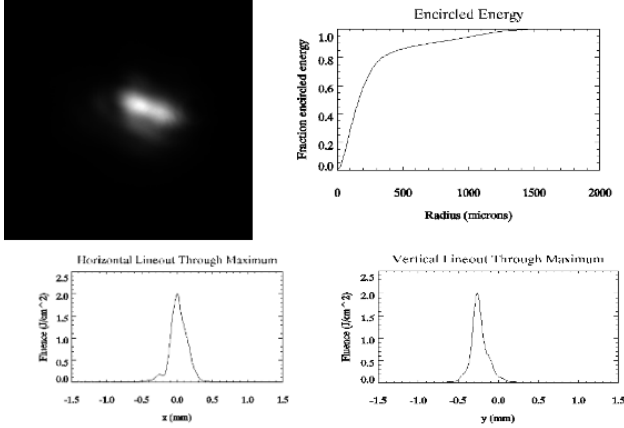

Fig. 7. a) 16-bit equivalent plane image of focal spot on sample. b) Encircled energy as a function of beam radius. c) and d) are spatial lineouts of the image in a).

IV. DAMAGE TEST PROCEDURES AND RESULTS

Several different procedures have been evaluated for the damage tests and assessing whether damage has occurred. In one method we expose the sample to 600 shots at a fixed fluence after which the sample is examined in a Nomarsky microscope and damage is defined as any visible change on the surface as in reference 1. Another method is to monitor the ratio of the diffracted energy to the input energy with any drop signifying damage. Because short-pulse damage has a very definite threshold with rapid and severe damage occurring at a fluence only a few percent above the fluence at which damage is first observable, these methods yield nearly identical damage thresholds.

The dependence of damage threshold on incident angle is particularly important to the design of several high-energy petawatt systems planned or under development at LLNL. The verification of the model prediction of the angular dependence was the first investigation conducted. The results are shown in figure 8. This grating had a groove density of 1800 l/mm. This early data was taken with a slightly earlier setup, the primary difference being the lack of a cross correlator to verify pulse duration. Nevertheless, the measurements showed an excellent agreement between the model and the experimental results.
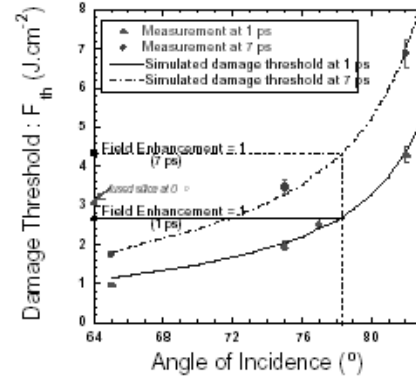

Fig. 8 – Damage threshold vs angle of incidence for an MLD grating for two pulse durations. Solid and dash lines are fits of experimental data with field-enhacement simulations based on the grating design. Damage threshold at normal incidence is given in comparison to the point where field-enhancement is equal to 1.

A large number of grating samples have now been tested with the PDTF. To date, most of our tests have focused on gratings with a groove density of 1780 l/mm used at an angle of 77°. The best performing grating of this type to date has a damage threshold of 3.0 J/cm^2. We are currently testing 20 gratings that have been manufactured at LLNL. Work is continuing to identify the grating design and manufacturing issues to push the envelope of future high-energy petawatt laser systems.

[1] R.D. BOYD, J.A. BRITTEN, D.E. DECKER, B.W. SHORE, B.C. STUART, M.D. PERRY, and LIFENG LI, "High-Efficiency Metallic Diffraction Gratings for Laser Applications," *Appl.Opt.* **34**, 10 1697 (1995)

[2] B.W. SHORE, B.C. STUART, M.D. FEIT, A.M. RUBENCHIK, and M.D. PERRY, "*Laser Induced Damage in Multilayer Dielectric Gratings due to Ultrashort Laser Pulses*," Proceedings of the First Annual International Conference on Solid State Lasers for Application to Inertial Confinement Fusion, SPIE **2633**, 714 (Monterey, CA 31 May – 2 June, 1995) Michel Andre and Howard Powell, Editors

[3] L. Li, "A Multilayer Modal Method for Diffraction Gratings of Arbitrary Profile, Depth, and Permittivity," *JOSA A*, **10**, 12 2581 (1993)